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THE PRIMARY CONCEPTS OF PHYSICS[1]

THE subject of the present address is one that does not often appear on a scientific program. Physicists are so busy in enlarging the structure of knowledge that few of them concern themselves with the consideration of the fundamental concepts of the science. Yet it is plainly true that if those fundamental or primary concepts are not clearly apprehended, or if there is doubt as to what they are, the whole structure of the science rests on an insecure basis. I propose to examine certain questions concerning these primary concepts, about which there has been and is much unsettled opinion. The discussion necessarily rests upon my own beliefs about them. In the nature of the case each man can speak positively about them for himself only. It would be very improper to dogmatize, and I shall accordingly have to crave your pardon for a frequent expression of my own opinion, believing it less objectionable to be egotistic than to be dogmatic.

The first question which I shall consider is that raised by the advocates of the dynamical definition of force, as to the order in which the concepts of force and mass come in thought when one is constructing the science of mechanics, or in other words, whether force or mass is the primary concept. It will be of service in the discussion if we consider briefly the way in which some of the great builders of the science of mechanics used these concepts.

[1] Presidential address delivered before the American Physical Society and Section B of the American Association for the Advancement of Science, at Washington, D. C., December 28, 1911.

There is no need of presenting the views of Archimedes or of Stevinus, whose work was exclusively in statics and who used the concept of force given us by our muscular or motor sense, and measured forces by weights. The views of Galileo, however, are interesting as showing how far one can go in dynamics without using the concept of mass.

Galileo examined the problem of the motion of a body acted on by a constant force. The only constant force of which he could dispose was the weight of a body, or a component of its weight, and he accordingly was limited in his studies to the examination of the laws of falling bodies. Owing to the relation of proportionality between the weight of a body and its mass, this limitation in a way simplified the problem, while at the same time it made it more difficult to develop a complete doctrine of force and motion. By the famous experiment at the Leaning Tower Galileo satisfied himself that he could study any falling body as a type, and that the conclusions which he would reach from that study would apply to all. His attention was therefore directed almost wholly to the consideration of the motion of the falling body, while the question of the relation between the motion and the weight of the body was disregarded. The result of this was that he developed the laws of linear motion with constant acceleration, and numerous consequences of those laws, chiefly relating to motion down inclined planes, with really wonderful completeness, and was led in the course of his thought to a full appreciation and statement of the principle of inertia, while yet he did not, in this part of his work, attain to any useful conception of the relation of force to mass. He makes it clear that the conception of force which is sufficient for his purposes is that with which he was familiar from his study of statics. He says, in speaking about the "tendency" of a body to fall down inclined planes of the same height, that "It is clear that the tendency of a body to fall is as great as the resistance or the least force which suffices to prevent its falling and to keep the body at rest." In fact Galileo thought of the weight of a body, with which he was familiar from common experience, as a force which moved the body, and assuming that the weight was unchanged during motion his experiments demonstrated what kind of motion such a constant force will set up and maintain.

In the very interesting discussion which Galileo gives of the forces exerted by the collision of one body against another, he approaches nearer than in other parts of his discourse to an appreciation of mass as a characteristic of a moving body. He speaks in one place of the falling body being a composite of weight and velocity, and his discussion of the impulse applied by such a falling body to another on which it falls shows that he was very near the concept of momentum; but there is no real precision in his statements.

We now turn to Newton to get the full doctrine of the relations of force and motion. It will be clear to any one who examines the introductory parts of the "Principia," that Newton did not undertake in that book to present a systematic treatise on dynamics. He merely blocks out a rough set of definitions and postulates, in a very uncritical way, which are sufficient to enable him to go on as promptly as possible to the real task which was before him. A striking instance of this uncritical attitude of mind is found in Definition I., in which he says, "Quantity of matter is its measure derived from its density and volume jointly." This quantity of matter thus defined he names

mass. Since we can only define density in terms of the concept of mass, it is surely uncritical to define mass in terms of density. In fact Newton on a later page uses the true definition when he says that bodies are of the same density if their *vires inertiæ* (that is, their masses) are proportional to their volumes.

The same sort of uncritical treatment appears in his presentation of the various types of force. He mentions first the *vis insita,* which he defines as the power of resisting, by which a body persists in its state of rest or of uniform motion. He says it differs in no respect, except in the way of conceiving of it, from the inertia of a mass.

Then comes *vis impressa,* the action (*actio*) exerted on a body to change its state of rest or of uniform motion. This is force in our ordinary sense. Newton says that it arises from a blow, from pressures or from centripetal force.

Vis centripeta is the force by which bodies are drawn or impelled from all directions toward any point as a center, or tend toward it in any way whatever. The force of gravitation and magnetic force are examples of this centripetal force. So also is the force by which a sling draws a stone in it toward the hand, which force Newton explains as arising from the stretching of the cord of the sling.

Newton then goes on to define the various measures or modes of giving quantitative expressions for centripetal forces. He first describes the *vis centripetæ quantitas absoluta* as the measure of it as greater or less by comparison with the efficiency of the cause which transmits it from the center through the surrounding region. Thus the magnetic force is greater in one magnet than in another, either because of the greater mass of the one or of the intensity of its power.

The *vis centripetæ quantitas acceleratrix* is the measure of it as proportional to the velocity which it generates in a given time. Thus the power (*virtus*) of a magnet is greater at lesser distances, and less at greater distances; gravitating force is greater in valleys, less on mountain peaks, and less still at greater distances from the earth. At equal distances, he says, this gravitating *vis acceleratrix* is the same everywhere, because all falling bodies are equally accelerated.

The *vis centripetæ quantitas motrix* is the measure of it as proportional to the momentum which it generates in a given time. This quantity is the center-seeking or tendency to the center of the whole body, and (as Newton says, with an evident appreciation that he is limiting the generality of his conception) is the weight of the body. It is always known by the force opposite to it, and equal to it, by which the fall of the body can be prevented.

Newton calls these quantities of force of the various sorts described by the shorter terms motive, accelerative and absolute forces, that is, he substitutes the general terms for the measured quantities of the forces which can be conceived only in those general terms. With this understanding he states that the *vis acceleratrix* is to the *vis motrix* as velocity is to momentum; for the quantity of motion (*momentum*) arises from the velocity and quantity of matter, and the *vis motrix* arises from the *vis acceleratrix* and the quantity of matter. For the sum of the actions of the *vis acceleratrix* upon the several particles of a body is the *vis motrix* of the whole body. Newton relates the *vis motrix* to a body as a striving of the whole body towards the center, made up of the striving of all its parts; the *vis acceleratrix* to the position of the body, as a certain efficiency, diffused from

the center through all places around it, for moving bodies which are in those places. The *vis acceleratrix* as thus described reminds us of the conception of the strength of a field of force.

This analysis of the concept of force surely does not promote a clear apprehension of it. The only one of the distinctions which have been made which seems to be worth retaining is that between the *vis impressa,* or action, and the *vis motrix impressa,* the one being force in its general or conceptual sense, the other the same force when given a measure or value. This distinction was clearly in Newton's mind and appears in the enunciation of the Laws of Motion. In the First Law the departure of a body from its state of rest or of uniform motion is ascribed to the *vis impressa;* that is, to force in general, without any specification as to its measure or even any declaration that it can be measured. In the Second Law the change of momentum is said to be proportional to the *vis motrix impressa;* that is, to force that is measured so that a proportionality to something else can be predicated of it. As has already been stated, Newton declared of this *vis motrix* in the special case of gravitation that it is known, or measured, by the force opposite to it and equal to it, by which the fall of the body, or, in the general case, the motion of the body, can be prevented. In the Third Law the force is called *actio.* This is the alternative word used in the definition of the *vis impressa,* as an equivalent for force in its general sense. The word in this sense is consistently used in the enunciation of the Third Law, in which forces are not considered as measured, but merely as compared by the condition of equality. From the examples of action and reaction which Newton gives (the finger pressed against a stone; the horse drawing a stone by a rope and drawn back equally toward the stone, because of the stretching of the rope and its exertion of equal forces at its two ends) it is plain that Newton conceived of forces in the way which is familiar to all of us, as the pushes and pulls which can be perceived by our motor sense, and as the causes of motions. He goes on to say that by these *actions* there are caused equal changes, not of velocity, but of momentum, so that the changes of velocity are inversely as the bodies (*corporibus*). In this way, without measuring forces, there is introduced the method of comparing masses.

It is difficult to perceive in these many definitions and declarations exactly what Newton's conception was of force, of the unit in which it is measured and of its relation to mass. After careful consideration of all that I can find in the "Principia" bearing on the question I am convinced that Newton viewed the concept of force as a primary one, or one directly given by intuition, and that he thought of the motions of bodies caused by these forces as connected quantitatively with them by the experimental relation embodied in the Second Law. Since Newton does not use a system of units, and states most of his laws and theorems in terms of proportions, the priority of force to mass, in the order of their apprehension, is not clearly presented.

In the matter of measuring a force he clearly asserts that a *vis motrix* is measured by the force which will counteract it and keep the body to which it is applied at rest, and the force thus used can hardly be other than a force measured statically; but his frequent insistence on the measure of *vis motrix* by the momentum which it causes shows that he had a conception also of the dynamical measure of force. He further supplies the measurement of mass as a fundamental quantity which is needed

to establish the dynamical measure of force by calling attention to the possibility of comparing masses by means of the velocities given them when acted upon by equal forces.

Lagrange in the "Mécanique Analytique" gives the most explicit expression to the definition of force in general which is the bugbear of so many thinkers, and which yet, after all, is the real expression of our belief about force, when he says:

We understand by force the cause, whatever it may be, which impresses or tends to impress a motion on a body to which we suppose it applied.

He goes on to say:

It should be measured by the quantity of motion impressed or ready to be impressed. In the condition of equilibrium, the force produces no actual effect; it produces only a simple tendency to motion; but it should be measured by the effect which it would produce if it were not restrained from acting.

Lagrange repeats this definition of the measure of force in the introduction to his "Dynamics," when he says that the product of the mass and the accelerating force (Newton's *vis acceleratrix*) or the acceleration, expresses the motive force (Newton's *vis motrix*). I can not find that Lagrange gives any definition of mass. From a statement in his treatment of centers of gravity it would seem that he considered the mass to be determined by its weight. He seems to endeavor to measure force in the purely dynamical way, without going into the matter as fully as he should for a complete elucidation of it.

Thomson and Tait say flatly that force is a direct object of sense, and define it as any cause which tends to alter a body's natural state of rest, or of uniform motion in a straight line. They assert that the measure of force is the quantity of motion which it produces per unit of time. They give no other definition of mass than the one given by Newton.

From the account which has been given of the views held or expressed by some of the great leaders of thought in matters of dynamics it is clear that very indefinite notions existed in their minds with respect not only to the proper definition of force, but even with respect to the proper measure of force, which is fundamental and necessary in the development of dynamics. The acute and valuable criticism by Mach of this fundamental notion is so colored in its expression by Mach's favorite principle of economy that it is not altogether satisfactory, and I accordingly shall attempt to present what seems to me the proper order of thought on this matter. Similar statements have been many times made, but there is still no general consent in the minds of physicists as to the statement which should be acceptable to every one.

There is no doubt that the dynamical *measure* of force is the correct one to use in building up a system of units. The point of difference on which dispute arises is the order of precedence of the two concepts force and mass in the establishment of this definition. It is not uncommon to have force defined as the product of mass by acceleration, or of mass by the acceleration which the mass would have if it were free to move. In this definition mass is the primary concept. Now, as I view the question, force is the primary concept, a direct object of sense, and we know it to be a cause of motion, or of the distortion of a body to which it is applied and which counteracts it when the distortion has reached a certain limit. In particular we know it as counteracting, or as being counteracted by, the weight of a body. This conception of force is adequate for the development of statics, in which we treat the principles of statics as statements of laws which are derived from experiment and confirmed by the proof that they are

mutually consistent. Galileo's experiments on falling bodies are then the direct experimental proof in a limited case of the proportionality between the force which acts on a body, measured at any one place by a weight, and the acceleration imparted to the body. Newton's Second Law is a statement of Galileo's discovery, with this addition, that the acceleration imparted by a force is not the same for all bodies, but depends upon a certain characteristic of the body. This characteristic, the mass of the body, first calls for recognition at this point. In the view I have taken the mass is the factor of proportion between the force which acts on a body and the acceleration which it imparts to the body. Since we can measure forces by comparison with a standard force, we can also measure masses by the aid of properly instituted experiments. Whether we measure masses in this way or not, and it turns out to be not a satisfactory way to do it, we at least get from this relation between force, of which we have a concept, and motion, of which we have a concept, an adequate working concept of mass. Force is the primary concept and mass is a derived concept.

Now owing to the permanency of masses of matter it is convenient to construct our system of units with a mass as one of the fundamental units. We are able to do this and to compare one mass with another chosen as standard, without going through the operation of measuring forces, by utilizing the principle embodied in Newton's Third Law. This law asserts that bodies which interact, that is, which exert forces on each other, exert equal forces, and thus, if the bodies are free to move, their acceleration will be inversely as their masses. By observation of the accelerations of two mutually interacting bodies we may thus compare their masses, and so construct a set or scale of masses, and use these masses and their accelerations to measure forces. Thus while the concept of force is primary in the order of thought, we may make the unit of mass fundamental in the development of a system of units.

The point upon which I wish to insist is that both reason and the history of mechanics show that the foundation of the science is the purely intuitional concept of force which is shared by every intelligent being, and that this intuitional concept is not only accurate so far as it goes, but adequate to serve as the foundation of a great science. No use of the concept of force in the theories of physics has ever violated in any particular this original and intuitional concept of it. Even the brilliant endeavor of Hertz to found all the principles of dynamics upon the three concepts of time, space and mass can not escape the criticism that the concept of mass is meaningless to us unless it is given to us by our experience of the inertia of matter when we exert force upon it. Once that concept is attained it may be used, as Hertz so beautifully used it, in the logical upbuilding of a system of dynamics. Perhaps my contention will be made clearer if we consider briefly the question whether it would be possible for us to construct our present system of dynamics if we were disembodied spirits, gifted with the means of observing spaces, times and colors, but without the sensation of force. We could see colored volumes, sometimes moving with constant velocity, sometimes with varying velocity, and we could ascribe the changing velocity to the action of a force. We further could connect the force with the moving volume by setting it equal to the acceleration multiplied by some factor which we might name the mass. This equation would contain two unknown and

unmeasured quantities, and would mean nothing unless we could go further. Now the advocates of the purely dynamical definition of the concept of force say that we can go further, by observing the mutual accelerations of two bodies and using these to obtain the ratio of their masses. If this can be done the matter is settled. But could it be done by the disembodied spirit? In our use of the mutual accelerations of two bodies to get their masses we must explicitly state that the bodies are arranged so as to interact (that is, to exert force on each other), and unless that condition is established the mutual accelerations of two bodies, however often repeated, can tell us nothing about their masses. A man at a station might observe two trains leaving the station in opposite directions with the same accelerations every day for ten years, and yet he could not compare their masses by any such observations. Eyes and mind only will not do it. To get the measure of mass we must start with the intuitional knowledge of force, and use it in the experiments by which we first define and then measure mass.

I now come to a much more difficult part of my subject, the consideration of the other primary concepts of space and time. Not many years ago we should have been willing to pass them over with a mere mention, admitting the impossibility of giving a definition or even an intelligible description of either of them, admitting the impossibility of determining an absolute or fixed point in space, or an absolute instant of time, but still asserting that we knew something about them both of which we were sure. At present we are driven by the development of the principle of relativity to examine anew the foundations of our thought in respect to these two primary concepts.

I suppose that the old ideas about space and time that have been of service to physicists since the beginning of the science are summed up as well as anywhere in Newton's words:

> Absolute and real time, the time of the mathematician, flows on equably, having no relation in itself or its nature to any external object. It is also called duration. Relative, apparent time, the time of common life, is an external measure of any duration cognized by the senses, by means of motion. It is commonly used in place of real time.
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> Absolute space, having no relation in its nature to any external object, always remains alike everywhere and immovable. Relative space is the measure of this space, or any movable dimension, recognized by our senses as limited by its situation with respect to bodies. This is commonly thought of as equivalent to absolute space.

These definitions have been often justly criticized for the emphasis laid on the unfruitful ideas of absolute time and space. Perhaps the criticism has fallen rather upon Newton's subsequent expansion of his thought on these ideas. But do they not contain in the first place the conceptions of time and space which have been uniquely useful up to this time in physics, and in the second place, do they not contain what each one of us really thinks about time and space when he makes an honest examination of his knowledge? The essential feature of both these descriptions for our present purpose is Newton's declaration, both as to time and space, considered as species and not as magnitudes, that they are in themselves and in their nature without relation to any external object. It is this statement which is contradicted by some of the enunciations of the principle of relativity.

It is not necessary for me to give an account of the genesis of the principle of relativity. It may fairly be said to be based on the necessity of explaining the negative result of the famous experiment of Michelson and Morley, and on the con-

venience of being able to apply Maxwell's equations of the electromagnetic field without change of form to a system referred to moving axes. It is not needed to explain many of the remarkable results obtained by Fizeau, by Mascart and by Brace, in the field of experimental optics, which to a first inspection seem to show that the earth and the medium around it through which light passes are relatively at rest, but which a closer study by Lorentz and others shows may be compatible with a reasonable theory of the structure of matter and the hypothesis that the luminiferous medium is at rest. It is also not needed to explain the dependence of the path of an electron in a field of crossed electric and magnetic forces upon its velocity, as exhibited in the beautiful experiments of Kauffmann and of Bucherer, for other theories in which the principle is not used lead to expressions for the path which, for the present at least, are in as good accord with observation as those which are deduced by the aid of the principle of relativity.

There are two ways of presenting the principle of relativity. In the first way the principle is stated as a direct inductive conclusion from the experiment of Michelson and Morley, and asserts that so far as a conclusion can be drawn from that experiment and the others which have been tried to test the matter, there is no way by which the relative motion of the earth and the luminiferous medium can be determined from observations made on the passage of light when the source of light and the observer are moving with the earth. As thus presented the principle holds out as the object of future study the construction of a suitable theory of the structure of matter and of the luminiferous medium to account for this fundamental experiment as well as for all other known truths in the domains of light and electricity. If this theory is expressed in terms of the Lorentz transformation, and thus shows a dependence of the measure of time and the measure of length upon the velocity of the system in which the observer is placed, it will further be the object of inquiry to construct a theory of the relations between the material of the system and the luminiferous medium which will account for the change in the units of length and in the motions of bodies by which the unit of time is determined. When I say to account for, I mean to describe in terms of force, time and space, as we conceive those notions in our every-day experience, and as we use them in our ordinary physical work, so that the description when apprehended will be reduced to the lowest terms in which our thought about the universe can be expressed. Such a description is, as I view it, a real explanation, and surely it is not yet time to say that such an explanation is impossible.

The other way of presenting the principle of relativity consists in laying down as a fundamental postulate a general proposition expressing the hopelessness of any attempt to settle the question raised by the experiment of Michelson and Morley by any theory of the structure of the universe. This postulate sometimes assumes a formidable aspect, and involves more than the mere postulate of relativity. Thus Laue says:

> The principle of relativity asserts that from the totality of natural phenomena we may, with continually increasing approximation, determine a system of reference, x, y, z, t, in which the laws of nature hold in a definite and mathematically simple form. This system of reference is by no means uniquely determined by the phenomena. There is rather a triple infinity of equally admissible systems, which move relatively to one another with uniform velocities.

The feature of this enunciation of the principle to which I referred as an addi-

tion to the principle is the expressed condition that in the system of reference the laws of nature hold in a definite and mathematically simple form. There is no warrant in the past history of physics for the adoption of such a postulate as that. Surely the history of the discovery of the so-called secondary laws of physics, such as Boyle's law, the laws of friction, the laws of polarization and of absorption of light, the laws of magnetization, and many others, will bear out the statement that in very many cases the first enunciation of the law is in a definite and mathematically simple form, and that further knowledge shows that this form is only a first approximation to the truth. Even in the case of such laws as the law of gravitation, or of electrical attraction and repulsion from which we have not yet detected any deviation, does any one dare to say that they are universally true for all bodies and at all distances? Can we even feel sure that Maxwell's electromagnetic equations hold true with absolute exactness? They need supplementing when they are applied to material bodies. Can we be sure that they hold without modification, in rapidly moving bodies, or at extremely minute distances in free space. Or, from another point of view, admitting that the object of physical study is to reduce the description of natural phenomena to a set of simple laws, have we a right to assume that, in our analysis of the structure of matter and of the luminiferous medium, we have as yet reached the ultimate model in which such simple laws will be operative? The answer to this question must be a negative one. Yet it is surely true that if it were not for this demand of simplicity, immediately attainable and at present expressed in the electromagnetic equations, the chief incentive to the development of the theory of relativity would be wanting.

But this is not the heart of the matter. With the principle of relativity as a basal postulate, not expressing our present inability, but rather the hopelessness of any attempt to obtain ability, a complete description has been given of the phenomena now known to physicists, at least in the domains of mechanics, light and electricity. The difficulty which I find in accepting the principle, with the universality that is predicated of it, is that it does so much more than this.

The theories of J. J. Thomson and of Lorentz made physicists familiar with the notion of electrical mass, exhibited by the variability of the mass of a moving charged body, or by the apparent variable inertia of a moving charge expressed as a function of its velocity, and further with the notion that as the velocity of the charge approaches the velocity of light the magnitude of the electrical mass approaches infinity, so that the velocity of an electrical charge, of an electron, and therefore presumably of matter, if it is entirely electrical in its structure, can never surpass the velocity of light. In these theories this remarkable conclusion was explained by the interaction between the moving charge and the ether. In the theory of relativity the same conclusion is reached as the consequence of a purely kinematical theorem, giving the rule for the addition of velocities, and not only does it hold for real moving charges, but for any action whatever which is conceivably transmitted through space. In particular this finite velocity of transmission must be ascribed to gravitational action. Now the Newtonian theory of gravitation assumes a practically infinite velocity of transmission of gravitational action, and astronomical observations have never given any warrant for the belief that its velocity of transmission is even of the order of mag-

nitude of the velocity of light. The attempt has been made to reconcile the theory of relativity with the observed motions of the planets by the adoption of an arbitrarily chosen term in the formula for the force on a planet to represent what is equivalent to a counteracting force to annul the tangential acceleration which would arise from the finite rate of transmission of gravitational force. This is manifestly an artifice and not an explanation. If the principle of relativity is of universal application, it should not need the introduction of such an artifice to help it out in the solution of one of the classical problems of physics.

Further, the principle of relativity in this metaphysical form professes to be able to abandon the hypothesis of an ether. All the necessary descriptions of the crucial experiments in optics and electricity by which the theories of the universe are now being tested can be given without the use of that hypothesis. Indeed the principle asserts our inability even to determine any one frame of reference that can be distinguished from another, or, what means the same thing, to detect any relative motion of the earth and the ether, and so to ascribe to the ether any sort of motion; from which it is concluded that the philosophical course is to abandon the concept of the ether altogether. This question will be amply and ably discussed this morning, but I may venture to say that in my opinion the abandonment of the hypothesis of an ether at the present time is a great and serious retrograde step in the development of speculative physics. The principle of relativity accounts for the negative result of the experiment of Michelson and Morley, but without an ether how do we account for the interference phenomena which made that experiment possible? There are only two ways yet thought of to account for the passage of light through space. Are the supporters of the theory of relativity going to return to the corpuscles of Newton? Are they willing to explain the colors of thin plates by invoking "the fits of easy reflection and of easy transmission?" Are they satisfied to say about diffraction that the corpuscles near an obstacle "move backwards and forwards with a motion like that of an eel"? How are they going to explain the plain facts of optics? Presumably they are postponing this necessary business until the consequences of the principle of relativity have been worked out. Perhaps there is some other conceivable mode of connection between bodies, by means of which periodic disturbances can be transmitted. We may imagine a sort of tentacular ether stretching like strings from electron to electron, serving as physical lines of force, and transmitting waves as a vibrating string does. Such a luminiferous medium would not meet the postulate of simplicity, but it conceivably might work. But whatever the properties of the medium may be, there is choice only between corpuscles and a medium, and I submit that it is incumbent upon the advocates of the new views to propose and develop an explanation of the transmission of light and of the phenomena which have been interpreted for so long as demonstrating its periodicity. Otherwise they are asking us to abandon what has furnished a sound basis for the interpretation of phenomena and for constructive work in order to preserve the universality of a metaphysical postulate.

The electromagnetic equations, too, the retention of which in their present simple form is the *sine qua non* of the promoters of the principle of relativity, were not only developed by the conscious use of the hypothesis of a medium in which the electric and magnetic forces exist, but can be inter-

preted intelligibly only in terms of some such medium. The abandonment of this hypothesis reminds one of Baron Münchausen's feat performed while he was making his escape from prison. Since your historical reading may not have extended to the autobiography of this famous man, I may be permitted to relate that the Baron was letting himself down from the windows of a high tower by a rope, and when he reached the end of it he found that he still had a long distance to go. The last part of the descent was particularly difficult, so to get rope enough he ingeniously spliced on an additional piece, which he obtained by cutting off the part above him.

The principle of relativity in its metaphysical form ignores the accelerations of bodies. It is true that the experimental results to which the principle has been applied with such success are such that the study of acceleration in terms of the theory of relativity has not become necessary. But is it not reasonable to suppose that when suitable experiments have been invented and tried to test the effect of the acceleration of a system on the progress of light in it, it may be found that an effect can be detected? Some effect may be detected, for example, due to the rotation of a body. I have never been able to perceive any sound objection to Newton's assertion that we have evidence of absolute rotation by the observation of centrifugal force, and if a fixed direction of an axis and an absolute velocity of rotation can be determined in a mechanical system when accelerations are taken into consideration, why should the principle of relativity be treated as having universal validity?

But, after all, these questions raised by the development of the principle of relativity are of secondary importance. The central question is whether or not this principle can ever furnish a satisfactory explanation of natural phenomena. The formulas derived from it are evidently merely descriptive. This may be said with truth about all the formulas in which the general theories of physics have been embodied. Kirchhoff designates, as the task of the science of mechanics, the description of the motions which occur in nature completely and in the simplest possible way. This assertion that the task of the theoretical physicist is done when he has reduced the phenomena with which he is dealing to a set of formulas, or, as we may say, when he has constructed an ideal model which will reproduce the phenomena, is one to which we would all assent in general. At the same time most of us would reserve the right to criticize each model thus presented, and to give to one or the other a preference based on considerations which are not necessarily limited to the simplicity of the model or to the completeness with which it reproduces the phenomena. Surely an additional test of the value of the model will be the intelligibility of the elements of which it is composed.

This last test has been generally met in the models which have been proposed as descriptions of natural phenomena. We can understand from what we see and feel what is meant by the motions of elastic spheres, and the model which uses them to represent the behavior of a gas is not only competent to reproduce the behavior of a gas, but is intelligible in the elements of which it is composed. The model of the elastic solid ether, incomplete and objectionable as it became when the subject of optics was enlarged and developed, was intelligible in its elements. The model of electromagnetic operations embodied in Maxwell's formulas is also one which is thus intelligible in its elements. When I say this I do not mean that we know all

about electric and magnetic forces, but I mean that we do know enough about such forces to have a clear notion of their variation in space and their variation in time.

This feature of the ideal model or description seems to me to be necessary in order to make the model acceptable as the ultimate or last attainable explanation of phenomena. The elements of which the model is constructed must be of types which are immediately perceived by the senses and which are accepted by everybody as the ultimate data of consciousness. It is only out of such elements that an explanation, in distinction from a mere barren set of formulas, can be constructed. A description of phenomena in terms of four dimensions in space would be unsatisfactory to me as an explanation, because by no stretch of my imagination can I make myself believe in the reality of a fourth dimension. The description of phenomena in terms of a time which is a function of the velocity of the body on which I reside will be, I fear, equally unsatisfactory to me, because, try I ever so hard, I can not make myself realize that such a time is conceivable.

Tried by this test, I feel that the principle of relativity does not speak the final word in the discussion about the structure of the universe. The formulas which flow from it may be in complete accord with all discovered truth, but they are expressed in terms which themselves are not in harmony with my ultimate notions about space and time. That this is true is so evident that it is generally admitted. Some writers say that we should not let this circumstance disturb us, because Kant has said that time and space are mere forms of perception, a scheme in which we must arrange occurrences so that they may acquire objective significance. I do not altogether understand what Kant meant by this, but I am sure he did not mean that by the exercise of our wills we can violently eject from our consciousness the notions of space and time which we have in common with the whole race of man, and impose on ourselves other and radically different notions. Planck compares our position before the new notions presented by the theory of relativity to the position of the medieval peoples before the notion of the antipodes. It seems to me that there is no real similarity between the two positions. Many men in the Middle Ages believed that there were no antipodes, but their belief was based on reasons, and so far were they from being unable to conceive of antipodes and to believe in their existence, that there were men who actually maintained their existence, and were pursued therefor as heretics. I do not believe that there is any man now living who can assert with truth that he can conceive a time which is a function of velocity or is willing to go to the stake for the conviction that his "now" is another man's "future" or still another man's "past."

One of the members of this society, recognizing our present inability to conceive of relative time, and conceiving our intuitions of space and time to be the result of heredity operating through many generations of men who lacked the light of relativity, once proposed to me that every one who could get even a glimmer of the notion of relative time should persistently exercise his mind therein and teach it to his students, in the hope that in a few generations the notion would emerge with the force of an intuition. It would not be fair to leave the impression that he was solemnly serious when he made this suggestion. When Matthew Arnold was asked to endure the transliteration of Greek names into English in order that the new forms might become familiar to future scholars,

he answered that he was not willing to spend his days in a wilderness of pedantry that his children might enjoy an orthographical Canaan; and *mutatis mutandis* the same answer may be given in this case. But a more pertinent answer is, to my mind, this, that the attempt to reorganize the perceptions of the human mind in respect to space and time is doomed to failure. "Which of you by taking thought can add one cubit unto his stature?" I believe that these ultimate perceptions are the same for all men now, have been the same for all men in the past, and will be the same for all men in the future. I believe, further, that this is true because the universe has a real existence apart from our perceptions of it, and that through its relations to our minds it imposes upon us certain common elementary notions which are true and shared by everybody.

Therefore, from my point of view, I can not see in the principle of relativity the ultimate solution of the problem of the universe. A solution to be really serviceable must be intelligible to everybody, to the common man as well as to the trained scholar. All previous physical theories have been thus intelligible. Can we venture to believe that the new space and time introduced by the principle of relativity are either thus intelligible now or will become so hereafter? A theory becomes intelligible when it is expressed in terms of the primary concepts of force, space and time, as they are understood by the whole race of man. When a physical law is expressed in terms of those concepts we feel that we have a reason for it, we rest intellectually satisfied on the ultimate basis of immediate knowledge. Have we not a right to ask of those leaders of thought to whom we owe the development of the theory of relativity, that they recognize the limited and partial applicability of that theory and its inability to describe the universe in intelligible terms, and to exhort them to pursue their brilliant course until they succeed in explaining the principle of relativity by reducing it to a mode of action expressed in terms of the primary concepts of physics?

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THE MOVEMENT FOR SCIENTIFIC INTERNATIONALISM AT THE HAGUE

PEDAGOGY lays ever greater emphasis on positive suggestion of the things that are good to do, rather than on negative prohibition of what is undesirable. The peace movement, as one of the biggest educational problems now in hand, is applying this principle in many ways. Everything which makes more evident the common interests of mankind tends toward peace as it awakens the larger loyalties which more and more take the place of primitive Chauvinism. The things which are specifically national are few and the things which are coextensive with human thought and human effort, many. If a realization of this fact were deep enough and wide enough men would altogether refuse to allow their interest and their public moneys to be diverted from the great common task, the advance of knowledge and its application to human welfare, by the little jealousies between groups which happen to live under different political organizations. The Foundation for the Promotion of Internationalism at The Hague has for its purpose the furthering of those movements for intellectual and social progress which are international in scope, and by so doing it plays an important part in the growth of the spirit of world peace.

It is obvious that, if such ends are to be realized, the efforts made must tend to meet practical needs in various fields of thought and action and not merely express a vague aspiration toward abstract ends. The Foundation for the Promotion of Internationalism has therefore addressed itself to a systematic study of the various movements for inter-